

S U N

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SUN

The Sun is a main-sequence star, one of over 100 billion stars in the Milky Way Galaxy. It takes the Sun over 200 million years to complete one orbit of the galaxy. It is located at present close to the Sagittarius-Carina spiral arm, in what is called the Orion spur.

The orbital trajectory is not planar, but undulating, the Sun passing through the principal plane of the galaxy once every ~ 30 million years. The planets of the Solar System revolve about the Sun in a plane normal to the Sun's circumgalactic trajectory. Thermonuclear reactions in the Sun's core convert hydrogen into helium, so that the helium fraction is progressively increasing through time. The reactions produce the energy to make the Sun a yellow-orange main-sequence star of spectral type dG2 (d indicates dwarf). The central temperature is about 15 million K; the surface temperature is about 6000 K.

The Sun is a nearly-perfect sphere of gas with a diameter of 1,400,000 km, held together by its own gravity. Its dimensions are at present not static and recent findings have shown that the Sun's diameter is at the present time decreasing about one meter every hour. This decrease may be a long-term oscillation which may be one effect of the long-term stabilization of the Sun's output of energy. It has also been found that every 2h 40min the Sun's surface pulses at a speed of 6 kmh^{-1} . Thus its surface moves in and out to change the diameter by nearly 10 km.

The Sun contains 99.86% of all matter in the solar system. It is the source

of light and heat for all planets and the support of life on Earth. A number of properties of the Sun is listed in Table 1-1 (cp. also Allen 1973; Lang 1980).

Solar Structure

Internal structure. The structure of the Sun is determined by the conditions of mass conservation, momentum conservation, energy conservation, and the mode of energy transport. The Sun is an oblate spheroid, like all the major bodies in the solar system, but in a first simplifying approach to describe the solar structure, the effects of rotation and magnetic fields will be neglected here so that the Sun is taken to be spherically symmetrical. Calculating a solar model means the determination of pressure, temperature and chemical composition as a function of mass or radius through the Sun, (Chandrasekhar 1967; Kourganoff 1973).

Two forces keep the Sun in hydrostatic equilibrium in its current stage of evolution: the gravitational force directed inward and the total pressure force directed outward. The equation of hydrostatic equilibrium is

$$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2}, \quad (1)$$

where P is the pressure, r the radial distance from the center, M_r the mass within a sphere of radius r , ρ the matter density, and G the gravitational constant. This equation is consistent with radius changes, but requires the kinetic energy involved in expansion or contraction of the solar body to be small compared to the gravitational potential of the Sun. For an order of magnitude estimate,

equation (1) can be written

$$\frac{dP}{dr} \approx \frac{P_c - P_o}{R_\odot} \approx \frac{P_c}{R_\odot} \approx \frac{GM_\odot \bar{\rho}}{R_\odot^2}, \quad (2)$$

where R_\odot is the solar radius, M_\odot the solar mass, $\bar{\rho}$ the mean matter density of the solar gas sphere, P_c is the central and P_o the surface pressure respectively, where the latter can be neglected.

The equation of mass conservation

$$\frac{dM_r}{dr} = 4\pi r^2 \rho, \quad (3)$$

constrains the integral of the density over the volume to be equal to the mass and leads to the estimation of the mean matter density for the Sun

$$\frac{M_\odot}{R_\odot} \approx R_\odot^2 \bar{\rho} \implies \bar{\rho}_\odot \propto \frac{M_\odot}{R_\odot^3}, \quad (4)$$

where the symbol \propto means “varies as”. In the general case, $\rho \propto M/R^3$, the constant of proportionality depends on the radial mass distribution and the radial distance R (Schwarzschild 1958; Haubold and Mathai 1987, 1992). Using eq.(4) and eq.(2), the central pressure of the Sun can be estimated to be

$$P_c \propto G \frac{M_\odot^2}{R_\odot^4}. \quad (5)$$

In the general case, $P \propto GM^2/R^4$, the constant of proportionality is determined by the radial distribution of mass in the Sun, and the particular radial distance R at which P is measured (Schwarzschild 1958; Haubold and Mathai 1987, 1992).

The interior of the Sun is entirely gaseous and the great majority of atoms are stripped of their electrons. The solar gas behaves under these physical conditions nearly like a perfect gas, governed by the “equation of state”

$$P = \frac{k}{\mu m_p} \rho T, \quad (6)$$

where m_p is the mass of the proton, k is Boltzmann’s constant, and μ is the mean molecular weight. This equation of state relates the pressure, temperature, density and chemical composition, and is related to other thermodynamic quantities. Then the central temperature of the Sun can be estimated from the perfect gas law in eq.(6), that is

$$T_c \approx \frac{\mu m_p}{k} \frac{P_c}{\rho} \implies T_c \propto \frac{m_p G}{k} \mu \frac{M_\odot}{R_\odot}. \quad (7)$$

This formula determines the temperature at the centre of the Sun according to its mass, radius and mean molecular weight of the solar matter. In the general case, $T \propto \mu M/R$, the constant of proportionality depends on the mass distribution and the radial distance R (Schwarzschild 1958; Haubold and Mathai 1987, 1992).

When X , Y , and Z are the mass fractions of hydrogen, helium, and heavy elements, respectively, then it holds by definition $X+Y+Z=1$. The mean molecular weight μ in eq.(6) can be calculated when the degree of ionization of each chemical element of solar matter has been specified. For solar gas composed of fully ionized hydrogen, there are two particles for every proton and it is $\mu = 1/2$. For a gas composed of fully ionized helium it is $\mu = 4/3$. For all elements heavier

than helium, usually referred to by astronomers as metals, it holds that their atomic weights are twice their charge and accordingly $\mu = 2$. Thus the mean atomic weight for fully ionized gas is

$$\mu = \frac{1}{2X + (3/4)Y + (1/2)Z}. \quad (8)$$

The solar matter is at present approximately 75% hydrogen, 23% helium and 2% metals by mass fraction. Throughout the solar interior, μ_{\odot} is approximately 0.59, except at the surface, where hydrogen and helium are not fully ionized, and in the core, where the chemical composition is altering due to nuclear burning (cp. Table 1-2) (Kavanagh 1972; Bahcall 1989).

An equation of continuity must also be satisfied by the radiation

$$\frac{dE}{dt} + \frac{dL_r}{dr} = 0, \quad (9)$$

where dE/dt is the rate of energy production per unit thickness of the shell of radius r . The equation of energy conservation is

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon = -\frac{dE}{dt}, \quad (10)$$

where L_r denotes the total net energy flux through a spherical shell of radius r and ϵ is the net release of energy per gram per second by thermonuclear reactions occurring in the gravitationally stabilized solar fusion reactor. It is assumed in eq.(9) that the energy produced by nuclear reactions equals the photon luminosity of the Sun, thus neglecting gravitational contraction and subtracting energy loss through neutrino emission. The mean energy generation

rate for the Sun can be inferred from eq.(10), that is

$$\bar{\epsilon} \approx \frac{L_{\odot}}{M_{\odot}}. \quad (11)$$

Finally the thermonuclear energy produced in the solar core is transported by radiation through the solar body to the surface. The force due to the gradient of the radiation pressure equals the momentum absorbed from the radiation streaming through the gas

$$\frac{dP}{dr} = -\frac{\kappa\rho}{c} \frac{L_r}{4\pi r^2}, \quad (12)$$

where $P = aT^4/3$ is the radiation pressure, κ is the opacity of the solar matter, $1/\kappa\rho$ is the mean free path of photons, and c is the velocity of light. The coefficient of the radiation density, a , is related to the Stefan-Boltzmann constant σ since $\sigma = ac/4$. Equation(12) is the energy transport equation taking into account the fact that energy transport in the deep interior of the Sun is exclusively managed by radiation. From eq.(11) follows the temperature gradient driving the radiation flux, that is

$$\frac{dT}{dr} = -\frac{3}{4ac} \frac{\kappa\rho}{T^3} \frac{L_r}{4\pi r^2}, \quad (13)$$

allowing an estimate of the solar luminosity

$$\frac{T_c}{R_{\odot}} \approx \frac{1}{ac} \frac{\kappa\bar{\rho}}{T_c^3} \frac{L_{\odot}}{R_{\odot}^2} \implies L_{\odot} \propto ac \left(\frac{Gm_p}{k}\right)^4 \frac{\mu^4}{\kappa} M_{\odot}^3, \quad (14)$$

taking into account eqs.(4) and (7). The luminosity is independent of the radius; it depends on the opacity and increases with mass. Eq.(14) is an important

result of the theory of the internal structure of solar-type stars, called theoretical mass-luminosity relationship. The fundamental result as given by eq. (14) is that the luminosity of the star is simply determined by its mass, since this rule is based on the fact that the transfer of energy from the stellar interior towards the surface is managed by radiation. The stellar energy sources must somehow adapt to the stellar opacity. The luminosity of a solar-type star is determined largely by photon opacity and not by the energy source.

Gamma-ray photons produced in thermonuclear reactions in the core of the Sun are being scattered, absorbed or re-emitted by free electrons, ions, and atoms on their way to the surface of the Sun. The opacity κ in eq.(12) is the measure of the solar material's efficiency at inhibiting the passage of the photons through the solar interior. The actual value of the opacity depends on various processes which may operate simultaneously: bound-bound transitions, bound-free transitions, free-free transitions, and scattering of photons by free electrons, ions and atoms. Scattering of photons by free electrons is the most important process for the solar core. Approaching the solar surface, bound-free transitions take over to determine the opacity of solar matter. The structure of the Sun depends in a sensitive way on the opacity, for if κ changes, the Sun must readjust all its parameters to allow the energy generated in the core to stream to the surface, not being blocked at any point in the solar interior.

Boundary conditions for the system of nonlinear differential equations (eqs.(1), (3), (10), (12)) have to be specified to arrive at specific solutions: At the solar

centre it is $r = 0, M_r = 0, L_r = 0$, and at the assumed solar surface (this is actually the photosphere) it holds $M_r = M_\odot$, and for an age of $t_\odot = 4.5 \times 10^9$ years, $r = R_\odot, L = L_\odot$. Mass, radius, surface temperature, surface chemical composition, and luminosity of the Sun are known by observation. Using the conservation laws and known properties of gases (equation of state, opacity, energy generation rates), the internal structure of the Sun can be calculated in matching the observed properties at the solar surface. However, because the equations of solar structure form a system of first-order nonlinear simultaneous differential equations, they have to be integrated numerically to obtain a very detailed picture of the run of physical variables throughout the Sun. Order of magnitude estimations provided in eqs.(4),(5),(7), (11) and (14) can be considered only to be a first approach to the problem (Mathai and Haubold 1988). Figure 1-2 shows the numerical results of a standard solar model based on the system of differential equations as described above (Sears 1964; Sackmann, Boothrayd, and Foulter 1990; Guenther et al. 1992).

Chemical composition changes with time (cp. eq. (10)) due to thermonuclear reactions in the solar core that results in a continuously evolving structure, the calculation of which adds another system of differential equations (kinetic equations) to the set of differential equations described above (Schwarzschild 1958; Kourganoff 1973).

core The core of the Sun is a gravitationally stabilized fusion reactor. There, energy is produced by conversion of hydrogen into helium. Each hydrogen atom

weighs 1.0078 atomic units and each helium atom is made from four hydrogen atoms thus weighing 4.003 atomic units. Accordingly, the difference of 0.0282 atomic units, or 0.7% of the mass m , is converted into energy E according to Einstein's formula $E = mc^2$, where c is the velocity of light. Most atoms in the core of the Sun are entirely stripped of their electrons by the high temperature and opacity is governed by scattering of photons by free electrons, by inverse bremsstrahlung on ionized hydrogen and helium, and by bound-free scattering by elements heavier than helium.

radiative zone The radiative zone is a region of highly ionized gas. There the energy transport is primarily by photon diffusion and is described in terms of the Rosseland mean opacity (this is a weighted inverse mean of the opacity over all frequencies, which can be used when the optical depth is very large and radiative transport reduces to a diffusion process).

convective zone In the outer regions, atoms may keep their electrons because of the low temperature and ions and even neutral hydrogen exist. Here many atomic absorption processes occur, mainly bound-free transitions. The high opacity makes it difficult for photon radiation to continue outward and steep temperature gradients are established which lead to convective currents. The outer envelope of the Sun is in convective equilibrium. It is the location where sunspots and other solar activity phenomena are generated. Observationally, the outer solar atmosphere following the convective zone has been divided into three spherically symmetric layers - the photosphere, chromosphere, and corona

- lying successively above one another (Zirin 1988).

photosphere The outer limit of the photosphere is the boundary of the visible solar disk as seen in white light. Most of the radiation emitted by the Sun originates in the photosphere, which is only about 500 km thick. This radiation is in equilibrium and the Stefan-Boltzmann law can be applied to calculate the effective temperature of the solar photosphere, which is $T_e = 5780K$. According to the Stefan-Boltzmann law each square centimeter of the solar surface having the temperature T emits, in all directions, light of σT^4 ergs per second. Subsequently, the total emission of the Sun in one second, i.e. the luminosity, equals

$$L_{\odot} = 4\pi R_{\odot}^2 \sigma T_e^4. \quad (15)$$

This fundamental relation also determines the radius of the Sun when its luminosity and surface temperature are known. The spectrum of the photosphere consists of absorption lines superimposed on an approximately blackbody continuum.

chromosphere A thin transition region extending 5000 km above the photosphere is called the chromosphere. Considerably hotter than the photosphere, the chromosphere is heated by hydromagnetic waves and compression waves originated by spicules and granules. The temperature of the chromosphere is about 10,000 K and it has an emission spectrum.

corona During a total solar eclipse the outermost atmosphere of the Sun can be seen. Called the solar corona (q.v.), this is a hot gas merging gradually

into the transparent interplanetary medium, and flowing outward from it is the solar wind. Current theories indicate that the corona is heated by the dissipation of mechanical energy stemming from the convection zone, or by dissipation of magnetic energy by field-line reconnection. The kinetic temperature of the solar corona is about $2 \times 10^6 K$ and its gas has a density of about $10^{-15} gcm^{-3}$. Solar x-ray radiation originates in the corona.

Solar activity. The Sun emits radiation in a wide range of the energy spectrum

from long radio waves (300m) to x-rays (0.1nm), including high-energy particles (cosmic rays q.v.). Almost 95% of the radiated energy is concentrated in a relatively narrow band between 250 nm and 2500 nm. The total radiation received from the Sun is called the solar constant; it was formerly regarded as a fixed value, $2.00 \pm 0.04 calcm^{-2}min^{-1}$, alternatively $1.36 \times 10^6 ergscm^{-2}s^{-1}$ (although difficult to measure), but from satellite observations it is now confirmed as a variable (up to about 0.5%) (Herman and Goldberg 1978; Sofia 1981; Schatten and Arking 1990). The transient phenomena occurring in the solar atmosphere can be grouped together under the term solar activity: sunspots and faculae occur in the photosphere; flares and plages belong to the chromosphere; and prominences and coronal structures develop in the corona. All solar activity phenomena are connected in this way or another with the 11 and 22-year sunspot cycle.

granules Granules are huge convective cells of hot gases, 400-1000 km in diame-

ter, spread in a cellular pattern over the entire photosphere except at sunspots. Granulation supports the transfer of energy from the convective zone outward into space. Granules behave as short-lived bubbles, lasting only 3 to 10 minutes, that rise and fall at a velocity of about 0.5 km s^{-1} , thereby moving vertically a distance of the order of 200 km.

spicules Spicules look like hairs of gas rising and falling at the upper chromosphere, reaching into the corona. They last as long as 10 minutes, attaining vertical speeds of up to 20 km s^{-1} getting upward to as high as 15,000 km. Spicules array themselves into chromospheric networks establishing giant supergranulated cells with gases rising in the center and descending at their outer boundaries.

sunspots Sunspots are relatively cool and dark markings on the Sun's photosphere, which exhibit distinct cycles. They are concentrations of strong magnetic fields (2000-3000 Gauss), with diameters less than about 50,000 km and lifetime of a few days to weeks. A sunspot generally develops a very dark central region, called the umbra, which is surrounded by the penumbra. The 11-yr sunspot cycle consists of variations in the size, number, and position of the sunspots (Fairbridge 1987a). It is extremely variable in length (actually, 7 to 17 yr.), the high-activity cycles (to ≥ 200 spots) are generally short (9-10 yr), and the low activity cycles (sometimes ≤ 50 spots) are long (12-13 yr). In the sunspot cycle the number of sunspots usually peaks 2-3 yr after the beginning of each cycle and decays gradually, but low activity cycles may have a reversed

symmetry. First spots of the cycle appear at higher latitudes, mostly between 20° and 35° , and as the spots increase in size and number they occur closer to the equator. Very few spots are observed outside the latitude range of $5^\circ - 35^\circ$. The magnetic polarity of the sunspot groups reverses in each successive cycle so that the complete cycle lasts 22 years, the so-called “Hale cycle”. Recent observations have indicated that the magnetic solar cycle is a coherent phenomenon throughout the solar surface. For each pair of 11-yr cycles, the one with north or leading magnetic orientation is usually stronger than the south one. Between 1645 and 1715 very few sunspots were seen, a time period called Maunder minimum. This period was associated with a long cold spell in Europe, known as Little Ice Age. Carbon-14 measurements from tree rings and Beryllium-10 measurements from arctic ice-cores confirm the low solar activity level at that time (Sonett 1984; Beer 1987, Fairbridge 1987b). The solar 11-year cycle has been recorded on a regular basis since the beginning of the 18th century classified by Wolf’s quantity N of the number of sunspots N_s plus ten times the number G of sunspot groups: $N = W(N_s + 10G)$, where W is a weighting factor assigned to an individual observer to account for variation in equipment, atmosphere conditions, and observer enthusiasm (Gibson 1973). The quantity N is widely used as an indicator of sunspot activity and is commonly called the Zurich sunspot number. More recently Bracewell (1989) was able to show that the quantity $N = \pm(N_s + 10G)^{3/2}$, with \pm denoting the dipole orientation, is nearly a sinusoidal function of time with a period of 22.2 ± 2 years. Using proxy

data for ancient sunspot periods (such as auroral frequency), the average of the 11-yr cycle is 11.12 yr, and thus coupled to the magnetic period.

prominences They are regions of cool ($10^4 K$), high-density gas embedded in the hot ($10^6 K$), low-density corona. Prominences can be observed as flamelike tongues of gas that appear above the limb of the Sun when observed in the light of the $H\alpha$ line. They occur in regions of horizontal magnetic fields, because these fields support prominences against the solar gravity, and indicate the transition from one magnetic polarity to the opposite.

flares Sunspots are accompanied by large eruptions called solar flares emitting high-energy particles and radiation in a very broad spectrum of energy. A solar flare is actually the result of an intensely hot electromagnetic explosion in the corona and produces vast quantities of x-rays which brighten the chromospheric gases. Typical lifetimes of solar flares are one to two hours and the temperature in flares can reach several million degrees. Flare particles ejected into outer space reach the Earth in a few hours or days and are the cause of disruptions in radio transmission. Aurora and magnetic storms are due to strong solar flare eruptions. The peak of solar flare activity is lagged by the sunspot cycle, usually 1-2 yr, but some high-energy eruptions may occur at any time ; the mean cycle of flare frequency is 0.417 yr.

Solar Rotation

Solar rotation was first accurately measured in the last century (in 1863) by R.C. Carrington (q.v.) who used the position of prominent spots as marker

points to determine a synodic period of about 27 days. Beginning from the first year of observation the solar rotations are indentified by “Carrington numbers”. The solar surface, however, exhibits differential rotation, as well as a coherent pattern of activity related to magnetic fields, and globally coherent oscillation modes. All three phenomena can be employed to shed light on the structure and dynamics of the Sun. Particularly helioseismology, the study of solar oscillation, made it possible to measure the depth of the solar convection zone, the internal rotation profile, the sound speed throughout the Sun, and the solar helium abundance, (Deubner and Gough 1984; Hill and Kroll 1992). Employing a standard model for the internal structure of the Sun, it has been shown with linear adiabatic perturbation theory that small-amplitude oscillations of the solar body about its equilibrium state can be classified into three types:(i) pressure modes (p-modes), where the pressure is the dominant restoring force; (ii) gravity-modes (g-modes), where gravity or buoyancy is the dominant restoring force; and a class of surface or interface modes (f-modes), which are nearly compressionless surface waves. The existence of all three modes has been confirmed by solar observations. The solar rotation rate through a large part of the solar interior has been estimated, utilizing for the most part observations of the p-mode frequency splittings. Each mode is characterized by an eigenfunction with frequency eigenvalue ν_{nlm} , where n , l , and m are integer “quantum” numbers; n counts the number of radial nodes in the wavefunction, and l and m describe the nodes in colatitude and longitude, respectively. Rotation breaks

the spherical symmetry of the Sun. Because of that the p-mode frequencies are not completely degenerate in m , and the frequencies ν_{nlm} in an nl -multiplet are said to be split in analogy to the Zeeman splitting of degenerate atomic energy levels. Because of observational limits it is not yet possible to observe values of splittings for individual m , to be used for inversion. However, results of observations are available in terms of coefficients $a_j (j \leq 5)$ of least-squares fits of the splittings

$$\nu_{nlm} - \nu_{nl0} = L \sum_j a_j(n, l) P_j^{(l)}\left(\frac{m}{L}\right), \quad (16)$$

where $P_j^{(L)}$ is a polynomial of degree j and $L = (l[l+1])^{1/2}$. The coefficients $a_j(n, l)$ of odd j reveal the information about the internal rotation of the Sun (Fig. 1-5). The analysis of observational data reveal that the latitude-dependent solar rotation profile as observed at the solar surface extends down through the convective envelope. In the radiative zone the rotation seems to have a solid-body profile. (Schou, Christensen-Dalsgaard, and Thompson 1992; Hill, Oglesby, and Gu 1992). To date there exists no obvious theoretical explanation for this helioseismologically inferred solar rotation profile.

Measurements of the individual frequencies of normal modes of the oscillating Sun may reveal the internal rotation profile. The ultimate goal of helioseismology is, however, to use all available pulsation data, including growth rates, phases, different modes - and not just observed frequencies - to search the internal structure and evolution of the Sun. Those data will definitely contribute to improve the inadequate treatment of convective transport of energy in the

envelope of the Sun by the mixing length theory as well as to solve the solar neutrino problem for the gravitationally stabilized solar fusion reactor. Eigenmodes of pulsations of different degree carry information of physical conditions in quite different parts of the Sun. High-degree modes (Figures 1-5 and 1-6) are restricted to solar sub-surface layers, where solar activity phenomena have their origin. Contrary to this, low-degree modes (Figure 1- 7) propagate all the way through the solar body to the regions where the solar neutrino flux is generated. Figures 1-5, 1-6, and 1-7 are equatorial cross sections from a model of the vibrating Sun (Weiss and Schneider 1991).

According to observation and theory of stellar evolution, young stars rotate rapidly. If the central part of the Sun still rotates rapidly, this should lead to a small oblateness in the Sun's disk, about 1 part in 10^5 . The extreme observational values reported for the solar oblateness lie between $5.0 \pm 0.7 \times 10^{-5}$ (Dicke and Goldenberg 1967) and $9.6 \pm 6.5 \times 10^{-6}$ (Hill and Stebbins 1975), with a proposal that this quantity varies with the solar cycle (Dicke et al. 1987). The oblateness of the Sun is still a hotly debated issue in observational and theoretical solar physics.

Solar Magnetic Field

All transient phenomena occurring in the solar atmosphere are connected with magnetic fields leading to a 22-year Hale cycle. To date all observed phenomena due to subsurface solar magnetic fields are inferred from the laws of

magnetohydrodynamics. In sunspots the magnetic-field lines are bundled and magnetic fields reach values of 2000 to 3000 Gauss. The mean magnetic-field intensity measurable at the solar surface is only approximately 1 Gauss. The small-scale features of magnetic activity on the solar surface are continuously changing with a degree of randomness as a result of complicated turbulent and ordered convective motions in the envelope of the Sun. The large-scale sunspot cycle, however, shows a well-defined behavior as a result of convection and generation of poloidal and toroidal magnetic fields within the differentially rotating Sun. Near the base of the convection zone the magnetic field may reach an amplitude of 10^5 Gauss.

The existence and generation of magnetic fields in the deep interior of the solar body is still a very controversial issue. The generally accepted view is that the convective envelope of the Sun is a converter of turbulence and differential rotation into an oscillating magnetic toroid and dipole. The magnetic field is confined to the convective envelope and is generated there by a dynamo mechanism, thereby consuming energy liberated by thermonuclear reactions in the gravitationally stabilized fusion reactor of the Sun. Energy generated in the core of the Sun is used to drive convection and differential rotation in the envelope of the Sun. Dynamo models successfully explain the periodic amplification of the solar magnetic field and the observed butterfly diagram of sunspots, respectively. Almost all these models rely on assumptions that employ stochastic mechanisms for the explanation of the 22-years solar activity cycle (Stix 1989).

Contrary to the stochastic approach to the generation of the solar magnetic field, it is possible in principle to explain the magnetic field as the result of the collapse of the primitive solar nebula. The radiative core of the Sun may have conserved its primordial magnetic field, locked into matter. It can be supposed that the radiative core of the Sun has a high electric conductivity conserving its low-order magnetic multipoles. Because a magnetic dipole existing in a fluid conductor is unstable towards a splitting along its symmetry planes and rotation about 180° , the dominant magnetic field in the core has a quadrupole configuration. This quadrupole model for the solar magnetic field could explain many of solar magnetic activity phenomena, but has not yet been confirmed by observations (Kundt 1992).

Solar Thermonuclear Energy Generation

The Sun shines because of the process of fusion where four protons fuse to form an alpha particle α , two positrons (e^+), and two neutrinos (ν_e), that is, $4p \rightarrow \alpha + 2e^+ + 2\nu_e$. In this fusion process of hydrogen nuclei into helium nuclei, the latter also known as alpha particles, the fusion can be accomplished through two different series of principal reactions: 98.5% of the energy generation in the present day Sun comes from the proton-proton chain (p-p chain); 1.5% of the solar energy output is due to the Carbon-Nitrogen-Oxygen cycle (CNO cycle). The p-p chain and the CNO cycle are shown in Table 1-3; there the third column indicates the percentage of the solar terminations of the p-p chain in

each reaction. Since the dependence of the energy generation rate ϵ (cp. eq. (8)) on the temperature is quite different between p-p chain and CNO cycle, the p-p chain dominates at low temperature ($T \leq 18 \times 10^6 \text{ K}$) (and the CNO cycle does not become important until high temperature is reached. At the present stage in the evolution of the Sun, the CNO cycle is believed to play a rather small role in the energy and neutrino production budget (Bahcall 1989).

In the first reaction of the p-p chain, a proton decays into a neutron in the immediate vicinity of another proton. The two particles form a heavy variety of hydrogen known as deuterium, along with a positron and an electronneutrino. There is a second reaction in the p-p chain producing deuterium and a neutrino by involving two protons and an electron. This reaction (pep-reaction) is 230 times less likely to occur in the solar core than the first reaction between two protons (pp-reaction). The deuterium nucleus produced in the pp- or pep-reaction fuses with another proton to form helium-3 and a gamma ray. About 88% of the time the p-p chain is completed when two helium-3 nuclei react to form an helium-4 nucleus and two protons, which may return to the beginning of the p-p chain. However, 12% of the time, a helium-3 nucleus fuses with a helium-4 nucleus to produce beryllium-7 and a gamma ray. In turn the beryllium-7 nucleus absorbs an electron and transmutes into lithium-7 and an electronneutrino. Only once for every 5000 completions of the p-p chain, beryllium-7 reacts with a proton to produce boron-8 which immediately decays into two helium-4 nuclei, a positron and an electronneutrino.

The net result of either the p-p chain or CNO cycle is the production of helium nuclei and minor abundances of heavier elements as ${}^7\text{Be}$, ${}^7\text{Li}$, ${}^8\text{Be}$, ${}^8\text{B}$ (in the case of the p-p chain) or ${}^{13}\text{N}$, ${}^{14}\text{N}$, ${}^{15}\text{N}$ (in the case of the CNO cycle). The energy generated by thermonuclear reactions in the form of gamma rays is streaming (actually, diffusing) toward the solar surface, thereby getting scattered, absorbed and reemitted by nuclei and electrons. On their way outward, the high-energy gamma ray is progressively changed to x-ray, to extreme ultraviolet ray, to ultraviolet ray and finally emerges mainly as visible light from the solar surface and radiates into outer space. Only the weakly interacting neutrinos can leave the solar core with almost no interaction with solar matter. However, the chlorine experiment of Davis and collaborators, the Japanese Kamiokande experiment, and the GALLEX experiment at Gran Sasso to detect solar neutrinos show that the Sun emits fewer of these elusive particles than the standard solar model predicts (Iben 1969; Lande 1989; Hirata et al. 1991; Anselmann et al. 1992 a,b). Since the beginning of the 70's this deficit challenges current understanding of solar and neutrino physics and of the process by which the Sun shines. The mystery of the missing solar neutrinos is commonly referred to as the “solar neutrino problem” (Bahcall and Davis 1982).

Solar Evolution

The general evolution scheme of the Sun postulates a progressive contraction of gas by self-gravitation which is periodically interrupted by thermonu-

clear burning. After particular types of nuclear fuel (hydrogen, helium) are exhausted, the contraction-burning cycle will be repeated, but at higher temperatures. The stages of the Sun's evolution from primitive solar nebula contraction to the black-dwarf stage can be followed in the Hertzsprung-Russell (H-R) diagram. There is a rapid movement of the Sun toward the main-sequence, where the Sun spends the major part of its life, and then an eventual movement toward the black-dwarf evolution stage, which is the final stage in its evolution (Schwarzschild 1958; Gibson 1973).

Presolar evolution stages. cloud Over 4.5 billion years ago, the gas cloud which would become the Sun had a diameter of over 480 trillion kilometers, which is approximately 50 light years. This cloud was not dense, containing only a few thousand atoms per cubic centimeters of space. The total mass of the cloud would have been sufficient for building up several solar systems. Its temperature was that of the interstellar space, of the order of 3 K, not radiating any light into the surrounding space. The fragile equilibrium state of the cloud, having only the choice of dissipating further into outer space or contracting into a denser configuration, eventually became disturbed either by an impact from outside or by random condensation of a large number of cloud particles, and finally began to condense.

globule After a time of the order of several thousand years, random concentrations of matter called globules formed at various places in the giant condensing matter cloud. The cloud collapses almost in free fall, however, due to the influ-

ence of pressure, the motion is non homologous. The free fall time of the cloud is

$$t_{ff\ cloud} = (\frac{3\pi}{32G\rho_0})^{1/2}, \quad (17)$$

where ρ_0 denotes the initial mean matter density of the cloud. The temperature in the cloud was rising very slowly, still not able to radiate light. Later, one of those globules, now having a dimension of several hundred solar systems, would become the Sun. The globule continued condensing with the effect of increasing its temperature.

protostar Within 400,000 years the globule had condensed to a millionth of its original size, but still over four times the size of the present solar system. At the centre of the globule a core had developed, heated by the concentration of its matter, already able to radiate a substantial amount of energy into the less dense outer regions of the former globule. The emission of radiation by the core began to slow the condensation of its matter. The matter becomes opaque and the free fall is stopped by the pressure. This core had now developed into a stable and well-defined configuration called protostar or protosun. With the birth of the protosun the evolution of this matter configuration advanced more rapidly. After the formation of a core, its free fall time is

$$t_{ff\ core} = (\frac{\pi^2}{8G} \frac{R^3}{M})^{1/2}, \quad (18)$$

where M is the mass and R the radius of the core, respectively. Within a few thousand years it collapsed to a size of the diameter of the orbit of planet Mars.

The interior temperature reached values of 56,000K leading to an ionization of atoms. The red light emitted at the surface of the protosun was not produced by fusion of atomic nuclei but by gravitational contraction of matter. Gravitation released the potential energy of the globule, $7 \times 10^{48} \text{erg}$, during the condensation of the protosun. According to the Virial theorem ($2T_k + \Omega = 0$) one half of the released gravitational energy Ω of the system was radiated from the protosun while the other half had been transformed into heat of the central core; T_k denotes the total kinetic energy of the particles.

Sun Finally the protosun contracted further until its temperature was high enough for burning deuterium to form helium-3. The Sun was fully convective in the contraction phase and the chemical composition was always uniform. Through deuterium burning the contraction was momentarily slowed down. As the Sun continued to contract, the central temperature increased and the radiative temperature gradient decreased relative to the convective gradient. Convection ceased and a radiative core grew outward. With the ignition of hydrogen the protosun became a star, characterized by the gravitationally stabilized fusion reactor located at its center. Its binding gravitational energy $|\Omega| \approx GM_\odot^2/R_\odot$ was initially stored in the extended globule, called the primitive solar nebula. If the sun would shine by its store of thermal energy $|T_k| = |\Omega|/2$ (Virial theorem), then its lifetime is given by the Kelvin- Helmholtz time scale, that is

$$t_{kw} = \frac{T_k}{L_\odot} \approx G \frac{M_\odot^2}{R_\odot L_\odot}. \quad (19)$$

As the nuclear reactions began to release vast amounts of subatomic energy, the

Sun was a quite variable star, varying in luminosity and surface activity as the result of the development of a radiative core and convective currents in its outer layers of gas. After a period of some 30 million years, its structure stabilized into the structure of a main-sequence star of one solar mass. The newly born Sun possessed enough fuel in the form of hydrogen to keep shining steadily for a time period of the order of

$$t_{nuc} = \frac{E_{nuc}}{L_{\odot}} \approx 10^{-3} \frac{M_{\odot} c^2}{L_{\odot}}, \quad (20)$$

where the factor 10^{-3} is due to the product of the percentage of mass of the Sun available for hydrogen burning (0.1) and the fraction of mass converted into energy in hydrogen burning $\Delta m/4m_p \approx 0.01$, where Δm is the mass difference in the net reaction $4p \rightarrow \alpha + 2e^+ + 2\nu_e$.

That means also that the present Sun is right in the middle of its age as a main-sequence star (4.5 billion years).

Postsolar evolution stages. red giant As the Sun ages, helium collects in its center. After a lifetime of 9 billion years as main-sequence star, approximately 10% of the hydrogen in the Sun's core will have been converted into helium and nuclear fusion reactions will cease producing energy. The equilibrium between the total pressure force directed outwards and the gravitational force directed towards the centre of the Sun will be disturbed. The core of the Sun starts slowly collapsing under its own gravitational attraction. Fusion moves outward to a shell surrounding the core, where hydrogen-rich material is still present. The gravitational energy from the collapse will be converted into

heat causing the shell to burn vigorously and so the Sun's outer layers to swell immensely. The surface is now far removed from the central energy source, cools and appears to glow red. The Sun now evolves into the stage of a red giant. For a few hundred million years, the expansion of the outer solar layers will continue, and the Sun will engulf the planet Mercury. The temperature on Venus and Earth will rise tremendously. Hydrogen fusion in the shell continues to deposit helium "ash" onto the core, which becomes even hotter and more massive.

In the Sun's core nuclear fusion of helium into carbon and oxygen will start to trigger even further the expansion of its outer layers. The helium-rich core is unable to lose heat fast enough and becomes unstable. In a very short time of few hours the core gets too hot and is forced to expand explosively. Outer layers of the Sun will absorb the core explosion but the core will no longer be able to produce energy by thermonuclear burning. Helium fusion then continues in a shell and the structure of the Sun would look like an onion: An outer, hydrogen-fusion layer and an inner, helium-fusion layer which surrounds an inert core of carbon and oxygen.

The old Sun may repeat the cycle of shrinking and swelling several times. In this stage of evolution the Sun is called an asymptotic giant branch star. Finally enough carbon will accumulate in the core to prevent the core explosion. Helium-shell burning will add heat to the outer layers of the Sun, mainly containing hydrogen and helium. The asymptotic giant Sun will generate even-

tually an intense wind that begins to carry off its outer envelope. The precise mechanism behind this phenomenon is not yet well understood. The Sun will expand a final time and after about 30 million years it will swallow Venus and Earth, outer layers will keep expanding outward and as much as half of the Sun's mass gets lost into space.

white dwarf The solar core keeps shrinking and because it is not able anymore to produce radiation by fusion the further evolution of this configuration is governed by gravitation. All matter will collapse into a small body about the size of the Earth. Thus, the Sun will have become a white dwarf, this is a dense-matter configuration, having radiated away the energy of its collapse. Then the white dwarf rapidly begins to cool.

black dwarf The final stage of solar evolution will be the black dwarf stage. The white dwarf will emit yellow light and then red light in the course of its evolution, drawing from the star's reservoir of thermal energy. Its nuclei will be packed as tightly as physically possible and no further collapse is possible. The body is progressively cooling down and finally becomes as cold as the interstellar space around it, emitting no light at all. As a carbon-oxygen-rich black dwarf it will continue its journey through the galaxy (milky way) and may eventually encounter another giant gas cloud to become involved in the birth of a new star.

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TABLE CAPTIONS

Table 1-1. A number of physical characteristics of the Sun.

Table 1-2. Internal structure of the Sun ($R_{\odot} = 6.96 \times 10^5 \text{ km}$)

Table 1-3. Principal reactions of the proton-proton-chain
and the CNO cycle in the Sun.

FIGURE CAPTIONS

- Figure 1-1. The beauty of the Sun. This snapshot from NASA's Skylap 4 (19 December 1973) shows one of the most spectacular solar flares ever recorded, spanning more than 588,000 km across the solar surface (Courtesy NASA Goddard Space Flight Center).
- Figure 1-2. A standard solar model of the present solar interior: $X = 0.708$, $Y = 0.272$, $Z = 0.0020$, $\rho_c = 158 g cm^{-3}$, $T_c = 1.57 \times 10^7 K$. (Courtesy of R.L. Sears of University of Michigan; Sears 1964).
- Figure 1-3. Schematic view of the structure of the Sun and modes of outward flow of energy (Courtesy NASA Goddard Space Flight Center).
- Figur 1-4. Solar interior rotation profile, as inferred from an inversion of p-mode splitting data, displayed at these latitudes: $\Theta_0 = 0^\circ$ (polar), $\Theta_0 = 45^\circ$, and $\Theta_0 = 90^\circ$ (equatorial). Dashed lines indicate 1σ error bars based on the observer's estimates of the uncertainties in the measured a_j coefficients (Courtesy J. Christensen-Dalsgaard; Schou et al. 1992).

Figure 1-5. Solar p-modes, equatorial cross section
 $l = 40, m = 40, \nu = 3.175mHz$ (Courtesy W.W. Weiss;
Weiss and Schneider 1991).

Figure 1-6. Solar p-modes; equatorial cross section
 $l = 40, m = 0, \nu = 3.175mHz$ (Courtesy W.W. Weiss; Weiss and
Schneider 1991).

Figure 1-7. Solar p-modes, equatorial cross section
 $l = 2, m = 2, \nu = 3.147mHz$ (Courtesy W.W. Weiss; Weiss and
Schneider 1991).

Figure 1-8. The path of a $1M_{\odot}$ star in the Hertzsprung-
Russel diagram.

TABLE 1-1 A number of physical characteristics of the Sun

Mean distance from Earth	1 astronomical unit (A.U.)= $1.496 \times 10^8 km$
Radius	$R_{\odot} = 6.960 \times 10^5 km$
Mass	$M_{\odot} = 1.991 \times 10^{33} g$
Mean density	$\bar{\rho}_{\odot} = 1.410 gcm^{-3}$
Gravity at surface	$g_{\odot} = 2.738 \times 10^4 cms^{-2}$
Total energy output (luminosity)	$L_{\odot} = 3.860 \times 10^{33} ergs^{-1}$
Effective surface temperature	$T_{eff} = 5780 K$
Solar age	$t_{\odot} = 4.5 \times 10^9 yr$

TABLE 1-2 Internal structure of the Sun ($R_{\odot} = 6.96 \times 10^5 km$)

Internal region	extension in terms of solar radius	chemical composition
core	$0.20R_{\odot}$	center only: He: 0.63, H: 0.35, metals: 0.02 (almost actively ionized matter)
radiative zone	$0.50R_{\odot}$	He: 0.23, H: 0.75, metals: 0.02 (highly ionized)
convective zone	$0.30R_{\odot}$	same (less ionized)
photosphere	$0.002R_{\odot}$	same (less ionized)
solar surface	$1.000R_{\odot}$	
chromosphere	0.02	same (less ionized)
corona	≈ 5	same (highly ionized)

TABLE 1-3 Principal reactions of the proton-proton chain and the CNO cycle in the Sun

Number	Reaction	Termination (%)	Neutrino Energy (MeV)
p-p chain			
1	$p + p \longrightarrow {}^2\text{H} + e^+ + \nu_e$	99.75	0.420 (spectrum)
	or		
2	$p + e^- + p \longrightarrow {}^2\text{H} + \nu_e$	0.25	1.44 (line)
3	${}^2\text{H} + p \longrightarrow {}^3\text{He} + \gamma$	100	
4	${}^3\text{He} + {}^3\text{He} \longrightarrow {}^4\text{He} + 2p$	88	
	or		
5	${}^3\text{He} + {}^4\text{He} \longrightarrow {}^7\text{Be} + \gamma$	12	
6	${}^7\text{Be} + e^- \longrightarrow {}^7\text{Li} + \nu_e$	99.98	0.861(90%) 0.383(10%) (both lines)
7	${}^7\text{Li} + p \longrightarrow 2{}^4\text{He}$		
	or		
8	${}^7\text{Be} + p \longrightarrow {}^8\text{B} + \gamma$	0.02	
9	${}^8\text{B} \longrightarrow {}^8\text{Be}^* + e^+ + \nu_e$		14.06 (spectrum)
10	${}^8\text{Be}^* \longrightarrow 2{}^4\text{He}$		
CNO cycle			
1	${}^{12}\text{C} + {}^1\text{H} \longrightarrow {}^{13}\text{N} + \gamma$		
2	${}^{13}\text{N} \longrightarrow {}^{13}\text{C} + e^+ + \nu_e$		1.2 (spectrum)
3	${}^{13}\text{C} + {}^1\text{H} \longrightarrow {}^{14}\text{N} + \gamma$		
4	${}^{14}\text{N} + {}^1\text{H} \longrightarrow {}^{15}\text{O} + \gamma$		
5	${}^{15}\text{O} \longrightarrow {}^{15}\text{N} + e^+ + \nu_e$		1.7 (spectrum)
6	${}^{15}\text{N} + {}^1\text{H} \longrightarrow {}^{12}\text{C} + {}^4\text{He}$		